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Life Cycle Analysis to estimate the environmental impact of residential photovoltaic systems in regions with a low solar irradiation

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ABSTRACT

Photovoltaic installations (PV-systems) are heavily promoted in Europe. In this paper, the Life Cycle Analysis (LCA) method is used to find out whether the high subsidy cost can be justified by the environmental benefits. Most existing LCAs of PV only use one-dimensional indicators and are only valid for regions with a high solar irradiation. This paper, however, presents a broad environmental evaluation of residential PV-systems for regions with a rather low solar irradiation of 900–1000 kWh/m^2/year, a value typical for Northern Europe and Canada. Based on the Ecoinvent LCA database, six Life Cycle Impact Assessment (LCIA) methods were considered for six different PV-technologies; the comprehensive Eco-Indicator 99 (EI 99) with its three perspectives (Hierarchist, Egalitarian and Individualistic) next to three one-dimensional indicators, namely Cumulative Energy Demand (CED), Global Warming Potential (GWP) and the Energy Payback Time (EPT).

For regions with low solar irradiation, we found that the EPT is less than 5 years. The Global Warming Potential of PV-electricity is about 10 times lower than that of electricity from a coal fired plant, but 4 times higher when compared to a nuclear power plant or a wind farm. Surprisingly, our results from the more comprehensive EI 99 assessment method do not correlate at all with our findings based on EPT and GWP. The results from the Individualist perspective are strongly influenced by the weighting of the different environmental aspects, which can be misleading. Therefore, to obtain a well-balanced environmental assessment of energy technologies, we recommend a carefully evaluated combination of various impact assessment methods.

Contents

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1. Introduction

Photovoltaic (PV) technologies are strongly supported in most developed countries, even in regions with a low solar irradiation such as Northern Europe. From a cost-efficiency perspective, this practice could be challenged for obvious reasons. When gas powered and nuclear electricity plants produce electricity at a production cost of some €75 per MWh, the diffusion of residential PV-installations with a production cost of some €300 to €450 per MWh in regions with a low solar irradiation [1] risks becoming extremely expensive. More and more authors recommend the immediate and drastic reduction of production subsidies (feed-in tariffs or green certificates) for solar technologies [2]. But can the support for PV-technologies also be challenged from a broad environmental perspective? Are there strong sustainability gains from investing in PV in regions with little sunshine? To answer the latter question, we perform a Life Cycle Impact Assessment (LCIA) for privately owned roof top PV-systems in regions with a low solar irradiation.

Table 1 presents some cities in regions with a low, moderate, and high solar irradiation. The data illustrates that investing in PV-systems in the south of Spain or California is much more interesting compared to Belgium, Germany or the U.K.

The analysis in this paper concerns regions with an irradiation of 900–1000 kWh/m^2/year, such as Belgium, the U.K., Germany and Sweden. Multiple Life Cycle Impact Assessment (LCIA) methods are compared to obtain a broad perspective on the environmental impact of residential PV-systems in those regions. All our calculations are based on the Ecoinvent (v2.0) database.

The LCA of PV-systems has been a subject of many articles, but in most cases, these assessments are limited to one-dimensional indicators such as Global Warming Potential (GWP), Cumulative Energy Demand (CED) and Energy Payback Time (EPT) [6–8]. PV is booming in countries such as Germany but unfortunately, only a few authors consider regions with low irradiation for their LCA. For example, Jungbluth [9] and Jungbluth et al. [10] have studied PV-systems in Switzerland, assuming an average horizontal irradiation of 1117 kWh/m^2/year, which is still some 15% more compared to the U.K., northern Germany and Belgium.

In this study, we want to contribute to the existing literature by comparing the results from the one-dimensional indicators, such as CED, EPT and GWP, with the Eco-Indicator 99 (EI 99) method for regions with a low irradiation (950 kWh/m^2/year). All the results are evaluated in detail and compared with data found in the literature. The goal is to obtain a very broad, nuanced and clear picture of the environmental impact of a residential PV-system.

Six different types of PV-systems will be evaluated: Cadmium Telluride (CdTe), $CuInSe_2$ (CIS), ribbon Si, multi crystalline Si (multi c-Si or poly c-Si), mono crystalline Si (mono c-Si) and amorphous (a-Si). Especially the new technologies such as CdTe and other thin film cell types have steep learning curves. The energy cost of thin film PV-cells is already comparable to that of crystalline systems [8] and has recently (end 2008) dropped to 1$/W [11]. According to Raugei and Frankl [8], the conversion efficiency is now at a satisfying 10–11% and could theoretically increase up to 16–17%.

In the next section, we present a brief overview of the different LCIA methods that were used. In Sections 3 and 4, the environmental impact of various PV-types is evaluated. We conclude by linking our findings to the existing literature and by discussing the value added of the EI 99 method. Table 2 gives an overview of the LCIAs used, and the technologies that have been analyzed.

Table 1
Horizontal irradiation in the EU, US and Canada (in kWh/m^2/year).

Low irradiation (kWh/m^2/year)		Moderate irradiation (kWh/m^2/year)		High irradiation (kWh/m^2/year)	
Brussels	960	Istanbul	1320	Seville	1700
Cologne	967	Bordeaux	1300	Cyprus	1750
London	980	Turin	1340	Malta	1770
Stockholm	940	Minneapolis (MN)	1430	San Francisco (CA)	1715
Vancouver	1100	Seattle (WA)	1200	Los Angeles (CA)	1788

Source: EU: [3]; US [4]; Canada [5].

Table 2
Overview of content of the paper and the used LCIA methods.

Unit	LCIA	Subject of research
3 kWp PV-system	CED, EPT, GWP, EI 99	CdTe/CIS/ribbon Si/multi c-Si/mono c-Si/a-Si
1 kWh electricity	GWP, EI 99	PV (multi c-Si) compared to fossil based energy

Table 3
Normalization and weighting factors for the three perspectives.

	Normalization			Weight		
	Hierarchist (H,A)	Egalitarian (E,E)	Individualist (I,I)	(H,A)	(E,E)	(I,I)
HH	0.0154 $DALYs_{(a)}$ (0,0)	0.0155 DALYs (0,0)	0.00825 DALYs (0,1)	40%	30%	55%
EQ	5130 $PDF_{(b)}$ m^2 year	5130 PDF m^2 year	4510 PDF m^2 year	40%	50%	25%
R	8410 MJ $surplus_{(c)}$	5940 MJ surplus	150 MJ surplus	20%	20%	20%

Source: Ecoinvent report n°3 [18]; PRé consultants [19].
(a) Disability Adjusted Life Years: years of life lost trough disability or early death; (b) Potentially Disappeared Fraction: % of plant species that disappear due to environmental load; and (c) Mega Joules surplus (increase in energy needed for resource extraction).

2. LCIA methods

2.1. Eco-Indicator 99

The Eco-Indicator assessment method (EI 99) was developed by PRé consultants in 1999 and offers a broad perspective on the environmental impact of a good or service. For this reason, many authors have used it to analyze the environmental impact of a wide variation of products, ranging from red clay [12] to beer [13], water-based UV-lacquers [14], desktop PCs [15] and wind turbines [16,17]. Two papers, by the same author, were found that applied the EI 99 assessment method to PV-systems [9,10].

In the EI 99 method, the environmental impact of a good or service is quantified using three main dimensions, namely: human health (HH), ecosystem quality (EQ) and the depletion of non-renewable resources (R).[3] The first step in the calculation of the overall environmental impact score is the quantification of the impact for these three dimensions. The unweighted results obtained in this first step are referred to as the "Characterization Results" and have different units (Table 3). To obtain a single score (with a single unit namely impact-points or eco-points) these results are then normalized and weighted (Table 3).

To cope with the issue of subjectivity in the weighting step, three different perspectives were developed: Hierarchist, Individualist and Egalitarian. Each perspective is based on a different ranking of preferences, values and attitudes (Table 4).

The weighting and normalization factors for the three perspectives (Table 3) used in the Ecoinvent database (Ecoinvent report n°3) are taken directly from the original report by PRé consultants (2001).[3] Notice the big difference between the normalization factor for resources used in the Individualist perspective (150 MJ), compared to the Hierarchist (8410 MJ) and Egalitarian perspective (5940 MJ). This difference in normalization will have a big impact on the results (see Section 3.4.2).

The *Individualist* does not consider the risk of a near fossil fuels depletion as credible [19]. To the Individualist, the only resource depletion that matters is mineral extraction. With a share of 20% in total impact, the amount of mineral extraction will have a big influence on the total score, especially for the production of PV-systems, which is quite mineral intensive.

The *Hierarchist* perspective is considered to represent the view of the 'average scientist', and is used as the default setting. The Hierarchist therefore follows the IPPC assessment reports to consider the effects of climate change [19, methodology report, p. 18].

The *Egalitarian* view pays more attention to future generations and is considered as rather risk averse. The Egalitarian looks at the very long term and puts a high value on ecosystem quality. This can result in risks being overestimated [19].

This discussion illustrates that the results of an environmental analysis should always be evaluated with care. PRé consultants, the developers of the EI 99 method, state that researchers should use the 3 different perspectives, and carefully compare the results. Sustainability and intergenerational equity are complex concepts and, by consequence, one should accept that sustainability assessments imply complex trade-offs. It is therefore crucial to thoroughly investigate the assumptions and weighting methods incorporated in the EI 99 method.

Publication of EI 99 scores without mentioning the conditions and weighting methods can result in serious misinterpretations. We recognize this issue and deal with it firstly by thoroughly explaining the calculation methods and secondly by publishing and evaluating not only the overall EI 99 scores, but also the unweighted characterization results.

As mentioned before, only two LCA-studies on PV-systems were found that applied the EI 99 method [9,10]. Jungbluth's first article [9] includes only crystalline PV-systems, and uses data from the year 2000. In the second article [10], also the new types were mentioned, but only the Hierarchist view is used. We add to the results by Jungbluth et al. [9,10] by applying the EI 99 method with the three perspectives to six different types of PV-system and adopting the Swiss results to be applicable to regions with lower solar radiation like the U.K. and Belgium. To have a better understanding on how the EI 99 results come about, the characterization results are also published and discussed. Furthermore, the three EI 99 perspectives are compared to each other, and to more commonly used indicators such as CED, GWP and EPT. This leads to six LCIAs for the six PV-technologies. To evaluate the consistency or the clustering of our results, we used a R^2 correlation test.

The GWP and EPT results are compared to results found in the literature, which are in most cases only valid for regions with a high irradiation (1700 kWh/m^2/year). These data from other authors were adapted to be applicable to regions with a low irradiation (950 kWh/m^2/year). To have an idea of the impact of the irradiation on the EPT, the values for low and high irradiation are compared. Finally, PV-systems are compared to other electricity technologies to obtain a better insight in how the use of PV-systems can reduce the environmental impact of electricity supply.

2.2. Global Warming Potential

The GWP assessment method, developed by the Intergovernmental Panel on Climate Change [20,21], is frequently used in energy research to investigate the impact of a product or a service on global warming [7,8,22–24]. Three GWP methods have been developed, each for a different time span (20 years, 100 years and 500 years). In this study the 100 years method was used. Using a different time span has no significant impact on the overall results.

2.3. Cumulative Energy Demand

The CED is a very popular LCIA method, especially in renewable energy technology research [6,25–28]. The CED aims to quantify all the energy that is consumed (or wasted) during the life cycle of a product. The CED is usually expressed in terms of primary energy (MJ_{prim}). In Ecoinvent, a different unit is used, namely energy equivalents (MJ-eq).

[3] http://www.pre.nl/eco-indicator99/ei99-reports.htm.

Table 4
General properties of the different EI 99 perspectives.

Perspective	Timeframe	Manageability	Evidence
Hierarchist (H,A)	Short and long term are balanced	Proper policy can avoid many problems	Based on consensus
Egalitarian (E,E)	Very long term	Problems can lead to catastrophe	All possible effects
Individualist (I,I)	Short term	Technology can avoid many problems	Only proven effects

Source: PRé consultants [19].

2.4. Energy Payback Time

The EPT is a frequently used parameter because of its input–output format and its ease to interpret. The EPT is, however, not straightforward to calculate. The formulas used to calculate the EPT are briefly summarized below (based on [6,22,29]).

The first step is to calculate the Yearly Energy Output (YEO) of the energy technology. There are two ways to do so. One starting from the Output Ratio (OR);

$$\mathrm{YEO} = \mathrm{OR} \times \mathrm{Power}[\mathrm{kWh/year}]$$

with OR = Output Ratio [kWh/kWp/year]; and Power = Total installed power, determined at STC[4] [kWp].

The other is based on Irradiation (R) and efficiency (θ);

$$\mathrm{YEO} = R \times A \times \theta \times \; p[\mathrm{kWh/year}]$$

with R = Yearly irradiation [kWh/m^2/year]; A = Active Surface of the PV-module [m^2]; θ = Conversion Efficiency [%]; and p = Performance Ratio [%].

The EPT can now be calculated by dividing the CED by the YEO, on the condition that both components are expressed in identical units (kWh or MJ[5] of *primary energy*). To convert the YEO from electrical energy to primary energy, one has to include the efficiency of the electricity supply in the region of interest. The Conversion coefficient (C) indicates how efficient the generation of electricity is, in a particular region [6,26]. In this paper, a Conversion coefficient of 0.35 [MJ_{el}/MJ_{prim}] is used.[6] Hence, we obtain EPT;

$$\mathrm{EPT} = \frac{\mathrm{CED}}{\mathrm{YEO}} \times C \quad [\mathrm{year}]$$

with CED = Cumulative Energy Demand [MJ_{prim}]; YEO = Yearly Energy Output [MJ_{el}/year]; and C = Conversion coefficient [MJ_{el}/MJ_{prim}].

It is remarkable that some authors do not incorporate the conversion coefficient [22,30], resulting in EPTs that are approximately 3 times longer.

3. LCA of a 3 kWp PV-system

3.1. Introduction

Based on the Ecoinvent database (version 2.0), an overview of the properties of the considered PV-technologies is presented in Table 5. The data from the Ecoinvent report n°6 [29] are compared with those from a recent article by Raugei and Frankl [8] (referred to as 'R&F, 2009' in Table 5).

Table 5 shows that mono c-Si and multi c-Si modules have the highest efficiencies, resulting in a lower active surface per installed power ratio (m^2/kWp). The data from Raugei and Frankl [8] and Ecoinvent (v2.0) are very similar, except for CdTe type systems (data in italic), which have a considerably lower efficiency according to the Ecoinvent report n°6. In this paper, the Ecoinvent 'module efficiency' will be used to calculate YEO and EPT.

To conduct our analysis, we made the following assumptions: the residential PV-systems are not integrated but installed on top of slanted roofs; a standard 3 kWp installation is considered; the output ratio for the PV-systems equals 725 kWh/kWp/year (a value typical for Belgium and the U.K. – compared to 848 kWh/kWp/year for Switzerland – Ecoinvent report n°6 [29], p. 128); the conversion coefficient (C) is 0.35 [MJ_{el}/MJ_{prim}]; the unit for CED is MJ-eq and the output ratio remains constant (module efficiency loss over time is not incorporated).

3.2. Cumulative Energy Demand and Energy Payback Time

3.2.1. Cumulative Energy Demand

The results of a CED analysis based on the Ecoinvent database for the different types of slanted roof, non-integrated, residential PV-systems are presented in Fig. 1. The CED is normally presented as a ratio: CED/kWp (MJ-eq/kWp) or CED/m^2 (MJ-eq/m^2). The results differ strongly according to the selected ratio. From an energy efficiency perspective, it is advisable to use the CED/kWp ratio, because it incorporates the differences in conversion efficiency.

According to the Ecoinvent database, the CED/kWp for CdTe, CIS and ribbon-Si PV-systems is less than 30,000 MJ-eq/kWp. The recent technologies appear to be more energy efficient than the 'old' crystalline Si-based technologies. As these new technologies have a steep learning curve, further significant energy savings can be expected. Mono c-Si, the oldest technology, has a high CED/kWp because of the energy intensive process that is required to produce the mono Si crystals [6]. As a result, the mono c-Si type is less attractive from an energy efficiency point of view.

3.2.2. Energy Payback Time

The EPT is calculated as explained in Section 2.4 (C = 0.35 [MJ_{el}/MJ_{prim}]). YEO and C are equal for all PV-systems, which results in EPT and CED/kWp being perfectly proportional (Fig. 2).

Our calculations, based on data from Ecoinvent (v2.0), show that the EPT is less than 5 years for all PV-types considered in this paper, installed in regions with a low irradiation (R = ±950 kWh/m^2/year; OR = 725 kWh/kWp). The impact of a different OR on the EPT is clearly visible, the EPT in Belgium/U.K. is about 4–5 years, in Switzerland (CH, OR = 848 kWh/kWp) it is about 3–4 years, and in Spain (ES, OR = 1282 kWh/kWp) it is reduced to only 2–3 years. The EPT for CdTe, CIS and ribbon Si, is about 1 year shorter than that of mono c-Si in regions with low irradiation, but this difference is reduced with increasing output ratios. In Spain, for example, the difference is only half a year.

Most authors mention a life expectancy of 25–30 years for well maintained PV-systems [8,28,31] As a result, the Net Energy Ratio (NER = lifetime/EPT) of PV-systems installed in regions with a low solar irradiation is about 5 (year/year). This means that a

[4] STC = standard test conditions (25 °C; 1000 W/m; AM 1.5).
[5] 1 kWh = 3.6 MJ or 3,600,000 J.
[6] Alsema and Nieuwlaar [6] claim that this is a commonly used figure for the conversion coefficient, this is also confirmed by other authors (Gürzenich and Wagner [26]).

Table 5
Properties of the PV-systems that will be investigated in this paper.

Cell type	Cell eff. (EI n°6) (%)	Module eff. (EI n°6) (%)	Module eff. (R&F, 2009) (%)	Active surface (EI n°6) (m^2/kWp)	Active surface (R&F, 2009) (m^2/kWp)	Weight (EI n°6) (kg/m^2)
Mono c-Si	15.3	14.0	14	7.1	7	14.6
Multi c-Si	14.4	13.2	13	7.6	8	14.6
Ribbon Si	13.1	12.0	11	8.3	9	14.6
a-Si	6.5	6.5	7	15.4	14	8.2
CIS	10.7	10.7	10	9.4	10	17.6
CdTe	*7.6*	*7.1*	*10*	*14.1*	*10*	*19.0*

Source: Ecoinvent report n°6, compared to properties mentioned by Raugei and Frankl [36].

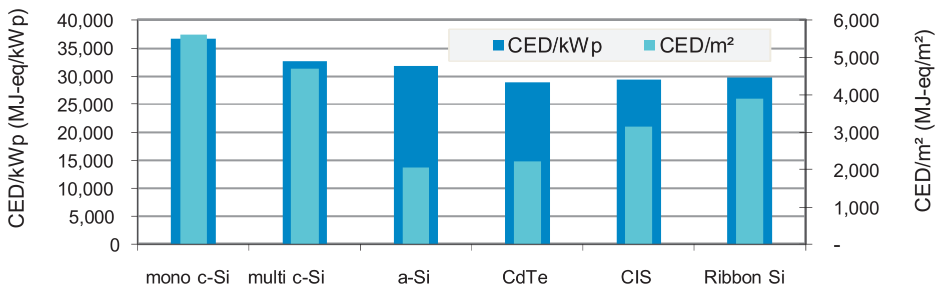

Fig. 1. CED/kWp and CED/m^2 for various types of residential 3 kWp PV-systems (Ecoinvent v2.0).

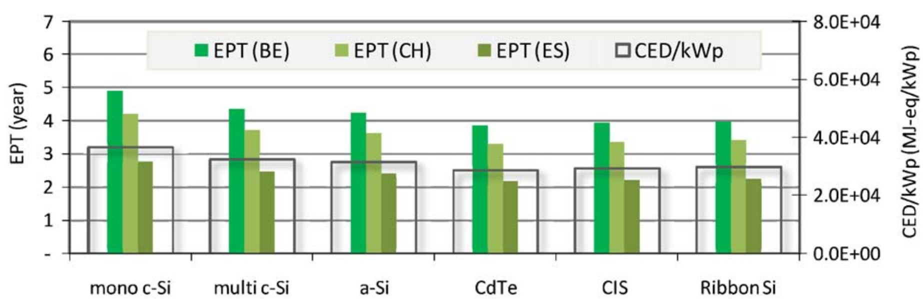

Fig. 2. CED/kWp and EPT for various types of residential 3 kWp PV-systems in different regions (Ecoinvent v2.0).

residential PV-system in Northern Europe or Canada can produce at least 5 times more energy than it consumed during its life cycle (mainly production). In sunny regions like Spain, PV-systems can even have NERs up to 12 (lifetime/EPT = 30 years/2.5 years = 12) or more.

3.3. Global Warming Potential

The GWP gives an indication of the amount of greenhouse gasses (GHGs) that are emitted during the life cycle of the PV-system. The results of the GWP analysis using the Ecoinvent database are shown in Fig. 3.

There are some differences between the GWP (kgCO_2-eq) and EPT (or CED/kWp) results. Consider for example the a-Si type PV-system; it has an EPT that is about the same as a multi c-Si PV-system. The GWP, on the other hand, is relatively high (±6000 kgCO_2-eq). Overall, the 'new' technologies such as CdTe, CIS and ribbon Si have the lowest impact on global warming (±5000 kgCO_2-eq for a 3 kWp rooftop installation). The correlation between the GWP, CED and EI 99 method will be discussed in Section 3.5.1.

3.4. Eco-Indicator 99

3.4.1. Eco-Indicator 99 (H,A)

To present a more comprehensive environmental impact assessment, we opted for the Eco-Indicator 99 (EI 99). The results found with the Ecoinvent database (v2.0), using the EI 99 Hierarchist (H,A) default perspective, are presented in Fig. 4. It is remarkable that the CdTe PV-system has the highest impact score (450 points)

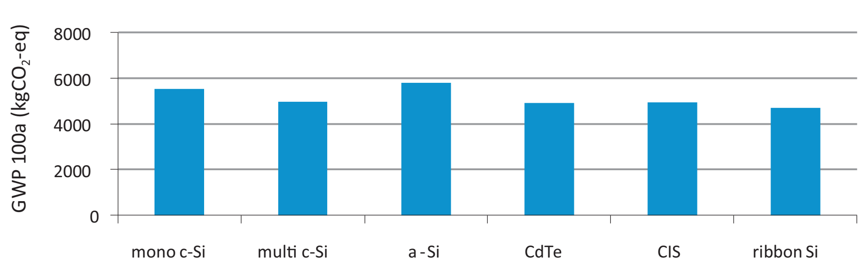

Fig. 3. GWP for various types of residential 3 kWp PV-systems (Ecoinvent v2.0).

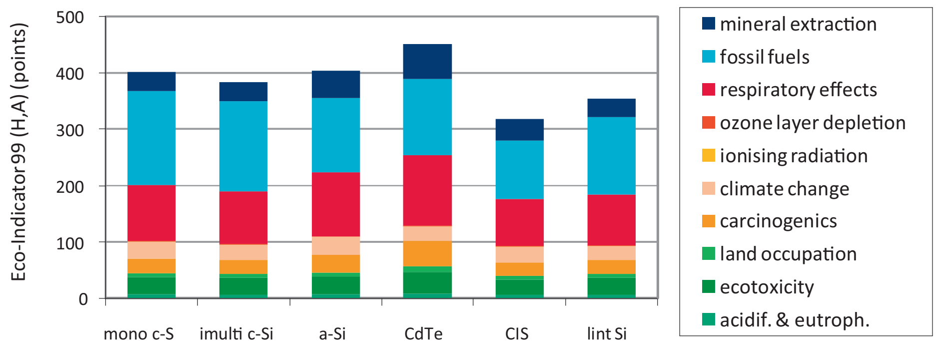

Fig. 4. Eco-Indicator '99 (H,A) results for various types of residential 3 kWp PV-systems (Ecoinvent v2.0).

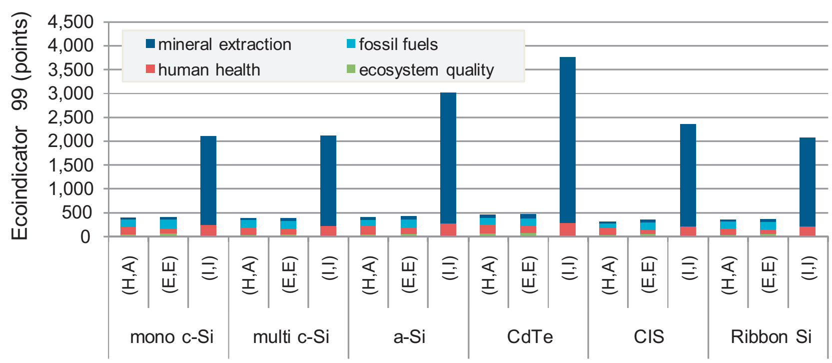

Fig. 5. Comparison of the EI 99 perspectives for various 3 kWp PV-systems (Ecoinvent v2.0).

according to the EI 99 (H,A), although the technology performed very well according to the GWP and EPT indicators. The other 'new' technologies, CIS and ribbon Si, have a much lower impact (317 and 353 points respectively). These findings are consistent with the results found by Jungbluth et al. [10].

The EI 99 method has the advantage that the different aspects of environmental impact can easily be visualized. Fig. 4 shows that depletion of fossil fuels and respiratory effects are the biggest contributors to the overall Eco-Indicator impact score. Fossil fuel extraction, respiratory effects, climate change, acidification and carcinogenics are closely related to each other, and to fossil energy demand [32]. Therefore, decreasing the energy use during production of PV-systems will decrease the impact of all of these factors [33].

3.4.2. *Influence of the used EI 99 perspective*

When the three different EI 99 perspectives are compared, the high scores resulting from the Individualist perspective are striking (Fig. 5). According to the Individualist, the high amount of mineral extraction necessary for the production of PV-systems is so important that other impact factors become negligible. The Individualist assigns high scores to CdTe (3764 points) and a-Si (3020 points).

The very high scores attributed to mineral extraction by the Individualist are due to the different ways by which resource depletion is normalized in the EI 99 method. The Individualist ignores fossil fuel depletion, which has as a consequence that all resource depletion is caused by mineral extraction. In the Hierarchist and Egalitarian perspective, resource depletion consists of both mineral extraction *and* fossil fuel use (see Fig. 5).

This difference in opinion about fossil energy has a big effect on the normalization of resource depletion as a whole. To give better insight in how these figures come about, the calculation method can be clarified with the following equation for all three perspectives:

$$\mathrm{Points}(H, A)/\mathrm{Norm}(H, A) = \mathrm{Points}(I, I)/\mathrm{Norm}(I, I) = \mathrm{Points}(E, E)/\mathrm{Norm}(E, E)$$

with Points(,) = EI 99 environmental impact-points according to a perspective and Norm(,) = normalization factor for a perspective.

Table 6 shows that the environmental impact-points for mineral extraction (ME) in the Individualist and the Hierarchist perspective are related in the same way as their normalization factors:

With: Norm ME (H,A) = 8410 MJ (Table 3).
Norm ME (I,I) = 150 MJ (Table 3).

Filling in the equation gives: Points ME (I,I) = 56.1 $\times$ Points ME (H,A).

In the Hierarchist and Egalitarian perspectives, total resource depletion is the sum of fossil fuel *and* mineral depletion, with fossil fuels being the main contributor (Fig. 5). The fact that fossil fuel depletion is also considered, gives rise to a higher normalization

Table 6
EI 99 environmental impact-points for mineral extraction according to the Individualist and the Hierarchist perspective (Ecoinvent v2.0).

Mineral extraction	Mono c-Si	Multi c-Si	a-Si	CdTe	CIS	Ribbon Si
A: EI 99 Points (H,A)	33.3	33.8	48.9	62.1	38.3	33.1
B: EI 99 Points (I,I)	1886	1896	2741	3483	2146	1855
B/A = Norm(H,A)/Norm(I,I)	56.1	56.1	56.1	56.1	56.1	56.1

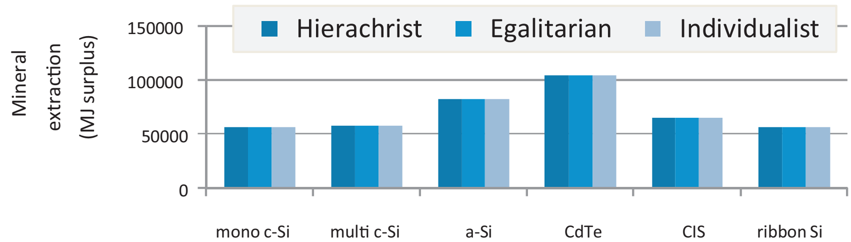

Fig. 6. Characterization results for mineral extraction (based on Ecoinvent v2.0).

factor (Table 3) and, as a consequence, a lower total impact score for resource depletion.

3.4.3. Characterization results

Since the influence of the normalization step on the end result is so large, we give up some of the simplicity of the single score method, to obtain more transparency. We do this by analyzing different aspects of the EI 99 method separately, using the characterization results. In Fig. 6 the characterization results for mineral extraction are given, this clearly shows that the impact of mineral extraction is the same for all perspectives and that the big differences in the final EI 99 score are caused by a difference in normalization factors only.

Fig. 6 shows that the use of Si and CdTe type modules clearly causes more impact on mineral extraction, compared to the other types of PV. This is probably due to their lower efficiency, which has as a consequence that more surface is needed to obtain a 3 kWp system. A grater surface results in more support structure and thus more metal usage.

According to Figs. 7 and 8, the impact on human health and the ecosystem is practically the same when using the Hierarchist or Egalitarian perspective. However, in contrast to the results for mineral depletion, the results from the Individualist perspective for human health and ecosystem impact are remarkably lower. This is not that surprising since the EI 99 methodology report [19] states that “In the individualist version, we choose to include only proven cause effect relations”. The Hierarchist and Egalitarian views, however, also consider generally accepted – but not fully proven – effects. This alternative (conservative) view by the Individualist partially explains the lower characterization results. Especially the low impact for eco-toxicity given by the Individualist is striking.

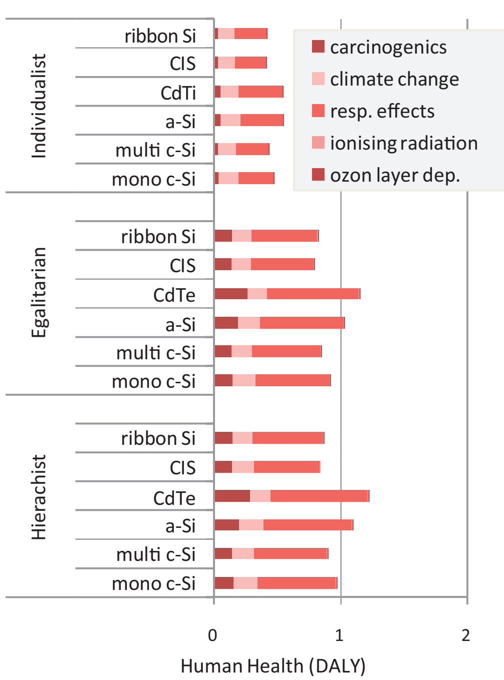

Fig. 7. Characterization results for human health impact (based on Ecoinvent 2.0).

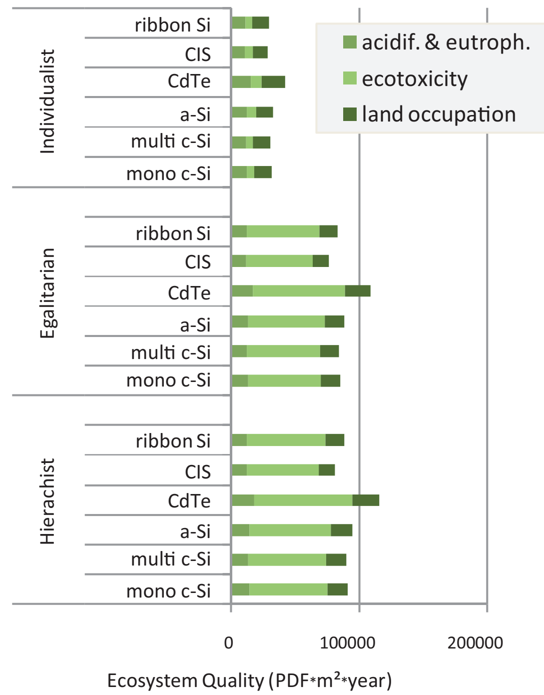

Fig. 8. Characterization results for ecosystem quality impact (based on Ecoinvent 2.0).

According to the Egalitarian and Hierarchist, the impact of a 3 kWp PV-system on human health is equal to 1 DALY, according to the Individualist however, this is only 0.5 DALY. All perspectives nevertheless agree that the biggest impact on human health is caused by respiratory effects, which is consistent with the results from the EI 99 (H,A) method (Fig. 4). In the case of eco-toxicity, the score given by the Individualist is about 50% lower compared to Egalitarian and Hierarchist scores. In general, the total impact is considered lower by the individualist.

Within the same perspective there are no big differences between different PV-systems, except for CdTe PV-systems which have a slightly bigger impact on human health and on the ecosystem, the former is due to a high score for carcinogenics, the latter mainly due to a higher impact on eco-toxicity.

3.4.4. Discussion

This analysis illustrates how a different perspective can strongly influence the results of a LCA. Irrespective of the results obtained by the EI 99 method, one can say that, clearly, the production of PV-systems comes with extensive mineral usage[7]

[7] More details can be found in the literature [7,34,35].

Table 7
Life cycle crude ore extraction of iron, aluminum and copper for a 3 kWp PV-installation (Ecoinvent v2.0) and total weight of a 3 kWp PV-system (calculations based on Ecoinvent report n°6).

Mineral Ore	Mono c-Si	Multi c-Si	a-Si	CdTe	CIS	Ribbon Si
Fe (kg)	103.23	106.50	189.13	112.94	77.43	77.22
Al (kg)	75.95	80.54	145.04	135.17	89.66	87.95
$Cu_{(d)}$ (kg)	25.30	25.41	26.37	39.44	24.14	25.56
Weight of 3 kWp PV-system (no BOS)						
Weight (kg)	311	333	379	804	496	364

(d) Is the sum of all the Copper ore types available in Ecoinvent (v2.0).

Table 8
R^2-test for the LCIAs used in this paper (calculations based on Ecoinvent v2.0).

Correlation (R^2)	CED/kWp	GWP	EI (H,A)	EI (E,E)	EI (I,I)
CED/kWp	–	0.53	0.02	0.00	0.22
GWP	0.53	–	0.07	0.12	0.00
EI (H,A)	0.02	0.07	–	0.91	0.50
EI (E,E)	0.00	0.12	0.91	–	0.73
EI (I,I)	0.22	0.00	0.50	0.73	–

(Table 7), even if most of the metals are assumed to be recycled (Ecoinvent report n°6).

The data in Table 7 indicate that the amount of mineral ore extraction needed for a 3 kWp rooftop PV-system is quite high, however, when compared to the weight of a 3 kWp PV-system, the results are not that surprising (Table 7). Removing the aluminum frames can significantly reduce the CED – and by consequence the environmental impact – of a solar panel (Alsema and Nieuwlaar [6]) but this is rarely done in practice.

3.5. Comparing different indicators and literature review

3.5.1. Comparing different indicators

When comparing CED, EPT, GWP and EI 99, it is clear that a combination of various methods is necessary to obtain a broad understanding of the environmental impact of the six PV-systems. We have performed a correlation test (R^2-test) to provide better insight in how the LCIA results for the six PV-technologies differ or cluster (note that CED/kWp and EPT are in our case perfectly correlated – see Fig. 2 – therefore EPT is not included in the comparison). The results of a full R^2-test of all the mentioned methods, and the characterization results is given in Appendix A. A summary of these results, mentioning only the CED/kWp, GWP and the three EI 99 perspectives is given in Table 8.

Table 8 shows that the correlation between CED/kWp or GWP and the three EI perspectives is at most 0.22. The correlation between CED/kWp and the Egalitarian EI 99 perspective is almost zero. These findings reveal that one-dimensional indicators are simply not comparable to more comprehensive indicators. One-dimensional indicators have of course a high relevance but we argue that the combination of one-dimensional indicators and more comprehensive indicators is preferable. The use of the characterization results instead of the EI perspectives themselves will not influence the result significantly, since they correlate highly with their respective EI 99 methods (See data in bold in Appendix A). It is remarkable to see that the correlation between EI 99 (I,I) and the characterization results for mineral extraction is almost perfect (0.999) this is not that surprising, given the high weighting of mineral extraction by the Individualist.

There is only a moderate correlation between the CED/kWp and GWP method (0.53) and a very high correlation (0.91) between the Hierarchist and Egalitarian view in the EI 99 method. Adding the Egalitarian perspective to an assessment with the Hierarchist perspective therefore has limited added value.

3.5.2. Energy Payback Time review

The CED and EPT of PV-systems have been popular measures to estimate the environmental impact of PV-systems in the past decades. A review of some results is given in Fig. 9. The EPTs were calculated based on the CEDs or EPTs mentioned in the cited publications. The results given here are adapted from the original results, in order to be applicable to regions with a low (950 kWh/m^2/year) or high (1700 kWh/m^2/year) irradiation.

This review illustrates that our results (based on Ecoinvent) are consistent with those from previous studies. Some of the data on which these results are based are implemented in the Ecoinvent database (v2.0). Authors like Alsema, Raugei, Pacca and Kato are frequently cited in the Ecoinvent report n°6. Some authors have used databases from others (with some adaptations) to estimate the CED and/or EPT values [30] instead of making an inventory themselves.

For reasons of compatibility and transparency, the system's performance ratio (p) was estimated to be 75% (also used by [6] and [31]) in all cases mentioned in Fig. 9. In other words, we assume that 25% of the produced electricity is lost in the inverter and cables. As mentioned before, the Conversion coefficient (C) was set at 0.35 [6,26]. Keeping all these parameters constant results in an EPT that is only influenced by Conversion efficiency (θ) and CED (see Section 2.4).

There are only 3 striking differences (EPT "low Irr" differs more than 2 years), namely:

- mono c-Si: Gürzenich and Wagner [26].
- a-Si: Pacca et al. [22].
- CdTe: Raugei et al. [36].

These 'outliers' were found in studies that mention several PV-types, from which only one of the EPTs in each study seem to be inconsistent with the Ecoinvent results. The EPTs published by Raugei [7,36] for CdTe PV-systems are much shorter than the EPTs that were found using the data in Ecoinvent. In the same year, 2 different EPTs for the same PV-type were published (one in a published article [7] and another in a conference proceeding [36]). If this reported EPT decline is a consequence of improved technology, than it is surely impressive. In this case, the EPT declines from 3 to 2 years in approximately 1 year's time.

The efficiency of a of CdTe module mentioned in the Ecoinvent report n°6 is rather low compared to the recent figures published by Raugei and Frankl [8] (data in italic in Table 5). In the case of CdTe, an efficiency increase from 7% (according to Ecoinvent) to 10% (Raugei and Frankl [36]) results in a decrease of the EPT by 30%. Also, a higher efficiency means that fewer modules are needed to obtain a 3 kWp installation. In this case, the total surface needed for a 3 kWp PV-installation decreases from 43 m^2 to 30 m^2, resulting in less support structure and again in a lower CED and EPT. An increase in efficiency can thus partly explain the low EPTs published by Raugei [7,36]. However, in a recent article by Ito et al. [27] the EPT is quite equal for all PV-types (EPT = 2–3 years with high irradiation), not indicating a shorter EPT for CdTe systems. Also, according to [27], when looking at the GWP, CdTe systems have properties comparable to the other PV-types (see below).

3.5.3. GWP review

In Fig. 10, our results for the GWP of a 3 kWp system obtained from ecoinvent are compared to those of a recent study by Ito et al. [27]. We can conclude that the GWP of a 3 kWp PV-system is about the same for all types of PV modules, and is situated around 5000–6000 kgCO_2-eq. It is important to mention that the PV-systems analyzed by Ito et al. [27] are not residential types but large scale

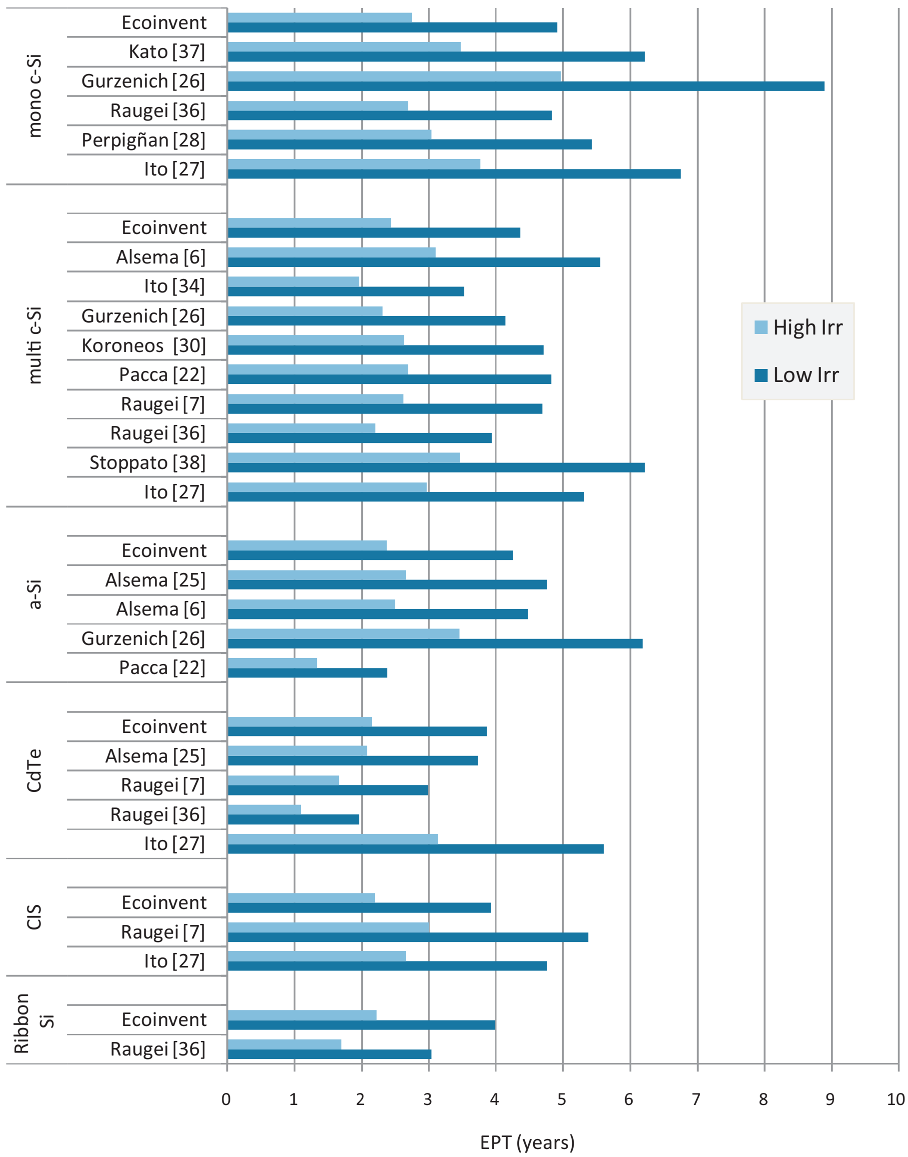

Fig. 9. Review of EPT's from previous publications and those calculated with Ecoinvent, adapted for a low and a high solar Kato [37] and Stoppato [38] irradiation.

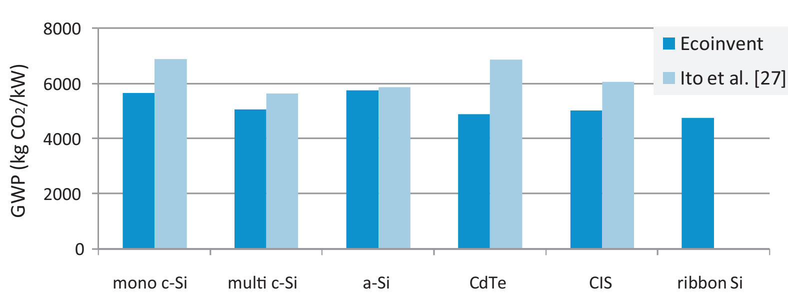

Fig. 10. GWP of a 3 kWp PV-system (Ito et al. [27] and Ecoinvent).

systems installed in the desert, nevertheless their results are comparable to ours.

4. LCA of 1 kWh of electricity

4.1. Introduction

The environmental impact of PV-systems is only relevant when compared to other energy technologies. To do so, the environmental impact caused by the production of 1 kWh of PV-electricity was estimated and compared to 1 kWh of electricity from other energy technologies.

To obtain the impact of 1 kWh of electricity, we can simply divide the impact of a 3 kWp PV-system by the Lifetime Energy Output (with YEO [kWh/year] = 3[kWp] × 725[kWh/kWp/year] = 2175[kWh/year]).

The Lifetime Energy Output is calculated as followed:

$$LEO = YEO \times lifetime[kWh]$$

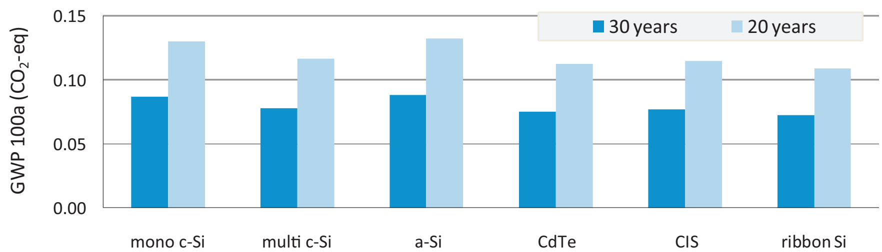

Fig. 11. Influence of the life expectancy of a PV-system on the GWP of 1 kWh of electricity for various types of residential 3 kWp PV-systems (OR = 725 kWh/kWp/year, Ecoinvent v2.0).

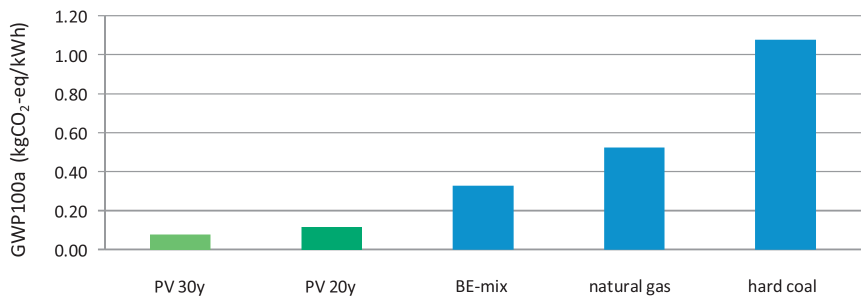

Fig. 12. GWP of 1 kWh electricity for various energy sources in Belgium (Ecoinvent v2.0).

with LEO = Lifetime Energy Output [kWh]; YEO = Yearly Energy Output [kWh/year]; and Lifetime = life expectancy of the PV-system [years].

In the Ecoinvent report n°6, a lifetime of 30 years is assumed. An IEA-PVPS report [14] also suggests to use a lifetime of 30 years. Some authors, however, suggest lifetimes of 20 or 25 years [38]. Therefore, in this paper, two lifetimes will be evaluated, a pessimistic estimate (20 years) and a realistic estimate (30 years).

The data for fossil energy sources are available in Ecoinvent and are used 'as such' without any adaptations. In this section, we select Belgium as an example of a country with a low solar irradiation. The environmental impact of a Belgian coal fired power plant, a Belgian gas fired plant and the Belgian energy mix is compared to that of PV-systems.

As it is meaningless to calculate the EPT for 1 kWh of electricity, only GWP and EI 99 are used to evaluate the environmental impact.

4.2. Global Warming Potential of 1 kWh of electricity

4.2.1. Global Warming Potential of PV-electricity

The results of the GWP analysis for 1 kWh of electricity, produced by a 3 kWp PV-system with a lifetime of 20 or 30 years are given in Fig. 11. The GWP for 1 kWh is, not surprisingly, perfectly proportional to the GWP of a 3 kWp PV-system (see Fig. 3).

The GWP of a PV-system that is used for 30 years (without efficiency loss over time, see assumptions in the introduction) is about 0.08 kgCO_2-eq/kWh, the GWP of a system that is used for only 20 years is about 0.12–0.13 kgCO_2-eq/kWh. It is clear that the life expectancy has a big influence on the GWP of 1 kWh of PV-electricity. The life expectancy should thus always be acknowledged when discussing the environmental profile of a PV-system, especially when one considers the wide range in lifetime (20–30 years) that was found in the literature.

Multi c-Si currently has the biggest market share [8], therefore this type was selected to represent PV-electricity when compared to other energy sources.

4.2.2. Global Warming Potential of 1 kWh of electricity

In Fig. 12, the results from the previous GWP analysis are compared to Belgium's current electricity technologies. The GWP is estimated for coal, natural gas and the average electricity mix in Belgium (BE-mix) in the period 2005–2007.

The difference between the GWP of 1 kWh of PV-electricity (multi c-Si type) and 1 kWh of fossil based electricity is striking. A natural gas power plant has a GWP of 0.53 kgCO_2-eq/kWh or about 7 times higher than the GWP of a PV-system with a life expectancy of 30 years (0.08 kgCO_2-eq/kWh). Even if the life expectancy of PV-systems is estimated to be 20 years, the GWP is still low (0.12 kgCO_2-eq/kWh), compared to fossil fuel based electricity generation.

The average kWh of Belgian electricity has a relatively low GWP (0.33 kgCO_2-eq/kWh). This can be attributed to the fact that 55% of the electricity in Belgium is produced by nuclear power plants that have a low CO_2-impact (GWP of 0.01 kgCO_2-eq/kWh [10]). A more general indication of the GWP for a mixture of various energy sources is the European electricity-mix (UCPTE-mix[8]), which has a GWP of 0.47 kgCO_2-eq/kWh [8]. This is about 5 times higher than a PV-system in a region with a low irradiation.

4.3. Eco-Indicator 99 analysis of 1 kWh of electricity

4.3.1. Comparing different perspectives

The results that were found using the EI 99 method for a 'residential 3 kWp PV-system' varied greatly depending on the selected perspective (see Section 3.4).

Fig. 13 shows that this observation remains valid for the comparison of different energy technologies. In order to simplify the results, only the three main impact categories (resource depletion, human health and ecosystem quality) are shown. In general terms, one can argue that resource depletion is the most important contributor to the overall environmental impact score, except for hard coal electricity generation, where impact on human health is more important.

The Individualist (I,I) prefers natural gas and finds that PV-systems have a big impact on resource depletion. The results in the Hierarchist (H,A) and Egalitarian (E,E) view are rather similar, with the exception of the impact score for hard coal. Coal will only become scarce in the very long term; this could explain the relatively high impact according to the Egalitarian view.

[8] Union for the Coordination of Production and Transmission of Electricity (EU).

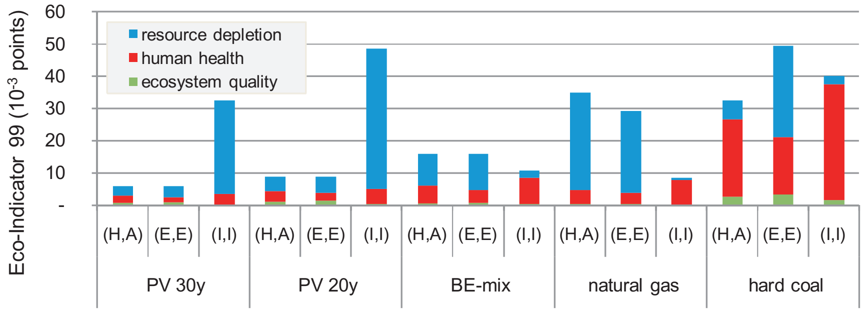

Fig. 13. Eco-Indicator 99 results for 1 kWh electricity of various energy sources in Belgium (Ecoinvent v2.0).

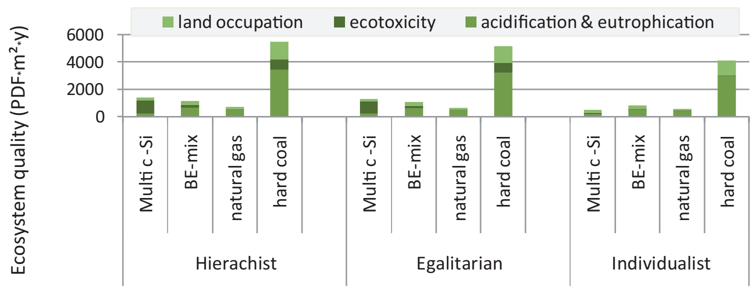

Fig. 14. Characterization results for Ecosystem Quality of 1 kWh of electricity (based on Ecoinvent v2.0).

The Hierarchist and the Egalitarian clearly prefer PV-systems as electricity sources instead of fossil based electricity production. The use of natural gas has much more environmental impact if fossil fuel depletion is considered to be unfavorable for future generations. This results in high fossil depletion impact scores for natural gas (0.03 points/kWh in Egalitarian view; 0.025 points/kWh in Hierarchist view).

The EI 99 impact score of 1 kWh of electricity from the BE-mix is about 3 times as high compared to PV (30 years lifetime) according to the Egalitarian and Hierarchist view. It is remarkable that the Belgian electricity mix has a relatively low score according to all the perspectives. This low impact is probably due to the high proportion of nuclear energy. These results suggest a low environmental impact for nuclear energy technology, according to Egalitarians, Hierarchists and Individualists, despite the fact that the impact of radiation is incorporated in the Human Health impact (see also next section).

4.3.2. Characterization results for 1 kWh of electricity

The characterization results for ecosystem quality, human health and resource depletion are given in Figs. 14–16 respectively. All the results are available in Appendix B. The multi c-Si PV-system is assumed to have a lifetime of 30 years.

When it comes to ecosystem quality, all perspectives agree that PV, natural gas and the BE-mix have a much lower impact compared to hard coal (Fig. 14). Notice that PV-electricity has a slightly higher impact on the ecosystem than the BE-mix, and twice as big an impact compared to natural gas (except in Individualist perspective). Remarkably, according to the characterization results of all perspectives, the eco-toxicity impact of PV-electricity is even larger than that of hard coal.

The impact on human health on the other hand is lowest for PV-electricity, even in regions with a low solar irradiation (Fig. 15). All perspectives agree that PV has a much lower impact on human health then coal, and about half the impact compared to gas. Notice that the damage to human health caused by ionizing radiation is very small for all electricity technologies, even the BE-mix, which has a share of nuclear energy of 55%. Almost all human health damage is caused by respiratory effects and adverse effects of climate change.

Fig. 16 shows that, when looking at the characterization results, the impact of mineral extraction is negligible compared to the impact on fossil fuel extraction. Looking at the characterization results from the individualist perspective, it is very remarkable to see that the MJ surplus caused by mineral extraction is very low and hardly visible on the chart. This graph shows very clearly that the high points in the EI 99 end score for the Individualist perspective (see Figs. 5 and 13) are caused by weighting and normalisation only, and that this has a very big impact on the overall results.

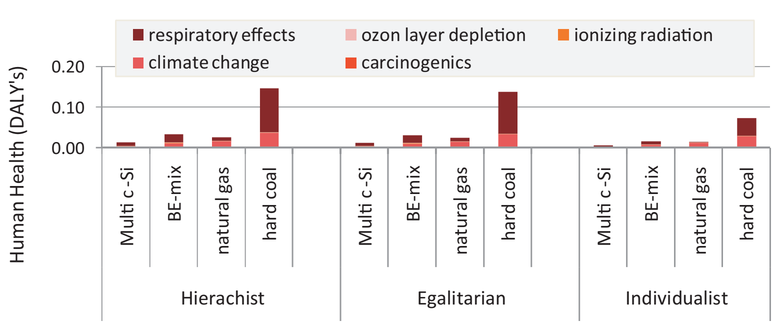

Fig. 15. Characterization results for Human Health of 1 kWh of electricity (based on Ecoinvent v2.0).

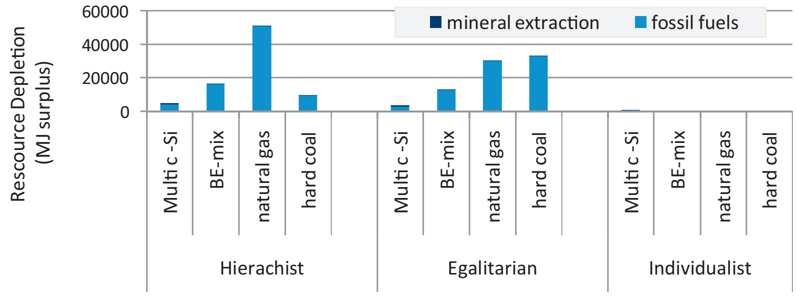

Fig. 16. Characterization results for Resource Depletion of 1 kWh of electricity (based on Ecoinvent v2.0).

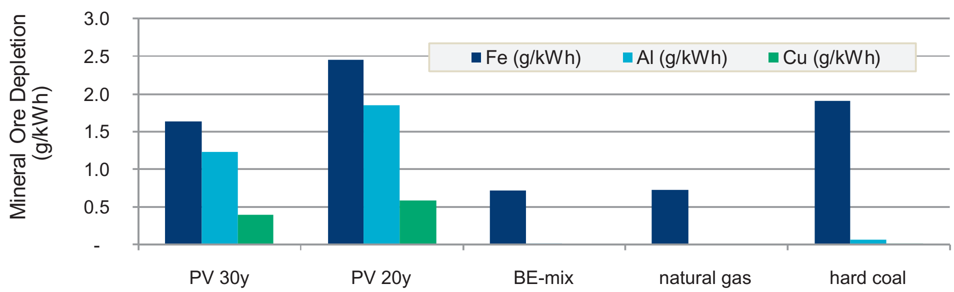

Fig. 17. Mineral ore depletion per kWh for various energy sources in Belgium (Ecoinvent v2.0).

Overall, PV-systems have a lower impact on human health, and have less impact on the depletion of resources. However, when looking at the ecosystem impact, PV-systems have a higher impact than a gas fired plant, but much less impact compared to a coal fired plant. The high impact on the ecosystem is caused by a large value for eco-toxicity (Fig. 14).

4.3.3. Mineral extraction for 1 kWh of electricity

The amount of mineral ore extraction per kWh of electricity for the various energy technologies is given in Fig. 17.

The results from the Ecoinvent database (v2.0) show that the amount of copper and aluminum ore extraction is much higher for PV-electricity, compared to the fossil based technologies and the Belgian electricity mix (with a high share of nuclear energy). This clearly indicates that PV has a big impact on mineral depletion, compared to the other technologies.

Comparing Figs. 13 and 17, it is clear that, according to the Individualist, the energy technologies that are very mineral intensive (such as PV and hard coal) have a high environmental impact. Technologies that need very small amounts of minerals, such as gas, have the lowest score.

4.4. Literature review and discussion

4.4.1. Global Warming Potential

The results presented in this article are similar to those found in the literature. Fig. 18 shows our results, based on the Ecoinvent database (multi c-Si PV-system, lifetime = 30 years), together with those from Jungbluth et al. [10], Pehnt [35], Raugei et al. [36] and Varun et al. [39].

One must be careful when comparing these results, because Varun et al. [39] have only considered CO_2-emissions as such, and did not use the GWP method that was developed by the IPCC. Varun's article contains a review of life cycle CO_2-emissions, for different renewable energy sources, and by various authors. These data show a wide variation, depending on the assumptions made. In Fig. 18, the average life cycle CO_2-emissions per kWh for PV and wind were calculated, based on the data found in Varun's review,

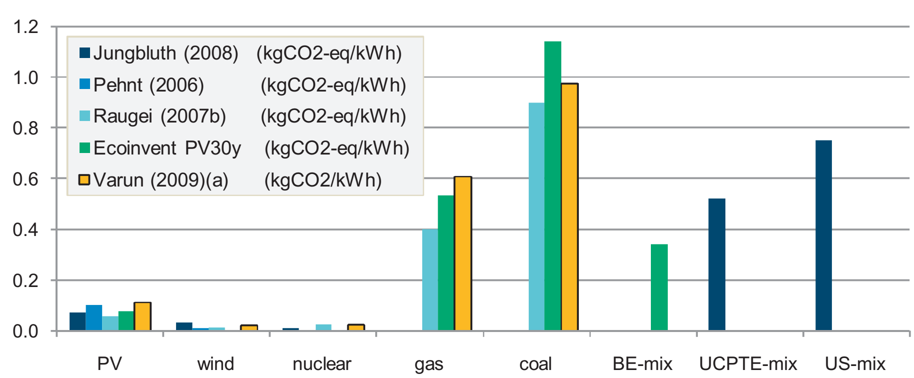

Fig. 18. Impact of renewable and other electricity sources (per kWh) on global warming according to various authors (a) results dating from before 2000 are not incorporated in the average for PV and wind.

Table 9
GWP of 1 kWh of electricity produced by PV (in regions with a low solar irradiation), wind and nuclear according to various authors.

	Ecoinvent PV 30 years ($kgCO_2$-eq)	Jungbluth [10] ($kgCO_2$-eq)	Pehnt [35] ($kgCO_2$-eq)	F&K [24] ($kgCO_2$-eq)	Raugei [36] ($kgCO_2$-eq)	Average ($kgCO_2$-eq)	Varun [39] ($kgCO_2$)
PV	0.08	0.07	0.10	0.06	0.055	0.07	0.112
Wind		0.03	0.01		0.011	0.02	0.021
Nuclear		0.01		0.022	0.024	0.02	0.024

results published before 2000 were considered to be out of date, and are not incorporated in the average. The CO_2-emissions for non-renewables were not calculated as a mean, but taken directly from the article (Tables 6 and 7, p. 1072, Varun et al. [39]).

Fig. 18 shows that PV, wind and nuclear have a very low CO_2-impact compared to the fossil based energy sources and the US and UCPTE electricity mixes. As mentioned before, the GWP of the Belgian electricity mix is relatively low because of the high share of nuclear energy. Roughly estimated, the GWP of PV-systems is 4 times higher than nuclear and 10 times lower than coal.

In Table 9, a review of the GWP of PV, wind and nuclear is given. These data illustrate the variations in GWP results and the very low GWP of wind and nuclear. Although the GWP of PV-systems and wind turbines is dependent on a variety of parameters, one can assume that in general, the GWP of wind and nuclear is about 1/4th of that of PV.

However, this result should be interpreted with care. A more detailed analysis of the GWP of nuclear energy by Ftenhakis and Kim [24] (F&K in Table 9) shows that the GWP of 1 kWh of nuclear-produced electricity can vary between 5 gCO_2-eq/kWh and 100 gCO_2-eq/kWh depending on the properties of the nuclear power plant and the assumptions made. In other words, in some cases, PV might have a lower GWP than nuclear. Also, in sunny regions, such as Spain or California, the GWP of PV-systems is much lower, and could be close to the GWP of wind or nuclear [36].

4.4.2. Eco-Indicator 99

In a recent article by Martinez [17] an EI 99 score of about 0.001 points is assigned to 1 kWh of wind energy from a 2 MW turbine in Spain. This is about 6 times less than the score we found for PV-systems in countries with a low solar irradiation, using the Hierarchist perspective (0.006 points for PV-systems with a life expectancy of 30 years). According to our results, PV-systems have good properties, but according to Martinez [17], the use of wind turbines has les environmental impact. Unfortunately, only one perspective was used by Martinez [17], the impact of different perspectives was not analyzed.

Jungbluth et al. [16] have compared the LCA results for wind turbines (800 kW onshore and 2 MW offshore) with those from PV-systems. In Jungbluth's paper, the three EI 99 perspectives were applied, unfortunately only relative results are given. By consequence, no conclusions relevant for this paper could be made.

4.4.3. Mineral extraction

Despite the fact that most of the metals are considered to be recyclable, the impact of PV-systems on mineral depletion is not to be ignored. Our results indicate that about 2 g of iron ore and 1.5 g of aluminum ore are needed for the production of 1 kWh of PV-electricity. An article by Pehnt [35] mentions comparable figures of 3.3 g of iron ore and 1.2 g of Bauxite (the most common Al-ore). If PV-systems are to become a major contributor to the electricity supply, an efficient recycling program would be advisable. Fortunately, this issue is receiving increasing attention.[9]

[9] For more information see http://www.pvcycle.org/.

4.4.4. Comparing different LCIAs

In this section, we analyze if the conclusions taken from the correlation test (R^2-test) in Section 3.5.1 are still valid when the energy technologies are very different. To answer this question, we repeated the R^2-test for the GWP and EI 99 results for multi c-Si (30 years), gas, coal and the Be-mix (see Appendix C).

The results indicate that the correlation is low in almost all cases, except for the correlation in between the characterization results (data in italic in Appendix C). Even the correlation between EI 99 scores and their related characterization results is low (data in bold), this, in contrast to the previous R^2-test that included only the 6 PV-technologies (Appendix B and Section 3.5.1).

Another remarkable difference compared to the results from Appendix A, is that the correlation between mineral extraction and the Individualist perspective is much lower (0.19 compared to 0.99), despite the high weight placed on mineral extraction by the Individualist. This result is largely attributable to the EI 99 results for hard coal electricity generation, for which the overall score given by the individualist is largely dominated by human health impact (see Fig. 13).

In other words, when the products are very similar to each other, the results from the EI 99 method is in good correlation with the characterization results. However, if the products are very different (like PV-systems and coal fired power plants) it is useful to look at the characterization results to obtain more insight in the EI 99 method.

5. Conclusion

In this article, the environmental impact of residential 3 kWp PV-systems, installed in regions with a low solar irradiation, is evaluated using six different life cycle impact assessment methods (LCIAs). Since most existing LCIAs for PV start from high irradiation levels and are based on one or two one-dimensional indicators, our work contributes to a more comprehensive assessment of PV-technologies. Next to critically evaluating the results, also the methods, especially the EI 99 method, are thoroughly evaluated and discussed. The results indicate that PV-systems have a relatively low environmental impact, even in regions with a low solar irradiation, especially when compared to fossil based energy sources. All the calculations are based on life cycle data from the Ecoinvent database (v2.0).

The EPT of residential PV-systems is less than 5 years in regions with a low solar irradiation, such as Belgium and the U.K. and about 2–3 years in regions with a high irradiation (such as the South of Europe and central/south U.S.). As most authors consider lifetimes of PV-systems to be at least 20 years, we can conclude that they are indeed a renewable source of electricity. The lifetime energy production is at least 4 times, and probably 6 times higher than the lifetime energy consumption. This could rise up to 12 times in sunny regions.

Since minimizing global warming is a frequently mentioned reason for governments to stimulate the use of PV-systems, the GWP of PV was estimated and compared to other energy technologies. We found that the GWP of 1 kWh of PV-electricity is about 0.08 $kgCO_2$-eq/kWh (considering a lifetime of 30 years),

which is lower than the current Belgian electricity mix (0.34 kgCO_2-eq/kWh) and the UCPTE-mix (0.47 kgCO_2-eq/kWh). These results are consistent with those found in the literature.

The EI 99 method with three perspectives offers a much broader perspective when compared to one-dimension indicators such as CED, GWP or EPT. The EI 99 results differ greatly depending on the used perspective. The Individualist view, that considers fossil fuels to be unlimited and only looks at the short term effects, puts a high weight on the amount of mineral extraction that comes with PV-production. According to the Individualist, gas fired power plants are a better option for electricity production than PV-systems. The Hierarchist and Egalitarian views, however, do consider the use of fossil fuels to have a negative impact on the wellbeing of future generations. According to these latter perspectives, PV-systems are a better option than gas or coal fired plants. The environmental impact of 1 kWh of PV-electricity was also smaller than the impact of 1 kWh of electricity from the average electricity mix in Belgium, according to the Egalitarian and Hierarchist perspectives.

However, the EI 99 method involves a weighting step that can be considered quite arbitrary. To obtain better insight in how the EI 99 scores come about, the characterization results are evaluated. When comparing these unweighted results with the (weighted) EI 99 scores, it is remarkable to see how big the impact of the weighting and normalisation step is, especially in the case of the Individualist perspective. One can argue that the very high weight that the Individualist gives to mineral extraction is far from what most people would consider to be logical or rational. This shows that one cannot overstress the fact that LCIA methods should always be evaluated with care.

A correlation test (R^2) applied to the LCIA results of the 6 different PV-types on the one hand, and the different electricity technologies on the other hand, clearly showed the added value of using multiple LCIAs. Therefore, we advocate the use of different LCIAs – including multi-dimensional ones such as EI 99 – in order to obtain a broad understanding of the impact of a process or product (such as PV). In our view, the benefits of the broader perspective are greater than the issues that might rise due to the over simplification of LCIA results. Since these issues can be overcome when the methods and assumptions are clearly defined and critically evaluated. Also, the comparison between the EI 99 scores and the (unweighted) characterization results is very informative, and can reduce the risk of misinterpretation.

In general, the properties of PV-systems seem to be very interesting from an environmental point of view. However, since about 1.6 g of iron ore and 1.2 g of aluminum ore are necessary for the production of 1 kWh of PV-electricity, the relatively high amount of minerals that are needed for the production of a PV-system should be acknowledged.

Appendix A

	CED/kWp	GWP	EI (H,A)	EI (E,E)	EI (I,I)	CR EQ (H,A)	CR EQ (E,E)	CR EQ (I,I)	CR HH (H,A)	CR HH (E,E)	CR HH (I,I)	CR Min
CED/kWp		0.53	0.02	0.00	0.22	0.06	0.06	0.23	0.02	0.02	0.00	0.23
GWP	0.53		0.07	0.12	0.00	0.01	0.01	0.00	0.06	0.06	0.22	0.00
EI (H,A)	0.02	0.07		0.91**	0.50	**0.81***	0.81*	0.80*	**0.82***	0.83*	0.73*	0.48
EI (E,E)	0.00	0.12	0.91**		0.73*	0.80*	**0.80***	0.71*	0.97**	**0.97****	0.91**	0.71*
EI (I,I)	0.22	0.00	0.50	0.73*		0.75*	0.75*	**0.80***	0.85*	0.85*	**0.71***	1.00**
CR EQ (H,A)	0.06	0.01	**0.81***	0.80*	0.75*		1.00**	0.99**	0.85*	0.85*	0.60	0.75*
CR EQ (E,E)	0.06	0.01	0.81*	**0.80***	0.75*	1.00**		0.99**	0.85*	0.85*	0.60	0.75*
CR EQ (I,I)	0.06	0.00	0.80*	0.83*	**0.80***	0.99**	0.99**		0.87*	0.88*	0.63	0.79*
CR HH (H,A)	0.02	0.06	**0.82***	0.97**	0.85*	0.85*	0.85*	0.87*		1.00**	0.92**	0.84**
CR HH (E,E)	0.02	0.06	0.83*	**0.97****	0.85*	0.85*	0.85*	0.88*	1.00**		0.91**	0.83**
CR HH (I,I)	0.00	0.22	0.73*	0.91**	**0.71***	0.60	0.60	0.63	0.92**	0.91**		0.68
CR Min	0.23	0.00	0.48	0.71*	1.00**	0.75*	0.75*	0.79*	0.84*	0.83*	0.68	

CR: characterization results; EQ: ecosystem quality: HH: human health; and Min = mineral extraction.

* $0.7 < R^2 < 0.9$.

** $0.9 < R^2$.

Appendix B

	Ecosystem quality (PDF m^2 year)			Human health (DALYs)					Resource depletion (MJ surplus)	
	Acidify. and eutroph.	Eco-toxicity	Land occup.	Carcinogenics	Climate change	Ionizing radiation	Ozone layer depletion	Respiratory effects	Fossil fuels extraction	Mineral extraction
(H,H)										
PV	208	**931**	241	2.244E−03	2.613E−03	7.541E−05	2.927E−06	8.774E−03	4142.2	871.9
BE-mix	619	217	285	5.720E−04	1.106E−02	2.265E−03	3.584E−06	1.970E−02	16577.8	69.3
Gas	497	30	135	8.505E−05	1.768E−02	4.050E−06	5.477E−06	9.112E−03	51026.8	20.6
Coal	3396	777	1293	1.807E−03	3.616E−02	7.356E−05	1.519E−06	1.095E−01	9717.1	77.3
(E,E)										
PV	195	**873**	226	2.189E−03	2.450E−03	7.070E−05	2.744E−06	8.262E−03	3116.5	871.9
BE-mix	581	203	267	5.363E−04	1.037E−02	2.123E−03	3.360E−06	1.852E−02	13226.0	69.3
Gas	466	28	127	7.976E−05	1.658E−02	3.797E−06	5.135E−06	8.591E−03	30376.0	20.7
Coal	3184	729	1212	1.694E−03	3.390E−02	6.897E−05	1.424E−06	1.029E−01	33447.0	77.3
(I,I)										
PV	179	**89**	207	4.817E−04	2.152E−03	2.537E−06	2.031E−06	3.985E−03	–	871.9
BE-mix	532	22	245	1.387E−04	9.065E−03	7.567E−05	2.490E−06	7.468E−03	–	69.3
Gas	427	3	116	2.075E−05	1.448E−02	1.363E−07	3.804E−06	1.016E−03	–	20.7
Coal	2919	87	1111	5.051E−04	2.965E−02	2.699E−06	1.057E−06	4.386E−02	–	77.3

Appendix C

	GWP	(H,A)	(E,E)	(I,I)	CR EQ (H,A)	CR HH (H,A)	CR EQ (E,E)	CR HH (E,E)	CR EQ (I,I)	CR HH (I,I)	CR Min
GWP		0.63	0.98	0.16	0.72	0.89	0.72	0.89	0.84	0.91	**0.41**
(H,A)	0.63		0.74	0.02	**0.13**	**0.29**	0.13	0.29	0.24	0.32	**0.65**
(E,E)	0.98	0.74		0.10	0.62	0.80	**0.62**	**0.80**	0.75	0.82	**0.45**
(I,I)	0.16	0.02	0.10		0.63	0.41	0.63	0.41	**0.48**	**0.39**	**0.19**
CR EQ (H,A)	0.72	**0.13**	0.62	0.63		*0.95*	*1.00*	*0.95*	*0.97*	*0.93*	0.04
CR HH (H,A)	0.89	**0.29**	0.80	0.41	*0.95*		*0.95*	*1.00*	*0.99*	*1.00*	0.17
CR EQ (E,E)	0.72	0.13	**0.62**	0.63	*1.00*	*0.95*		*0.95*	*0.97*	*0.93*	0.04
CR HH (E,E)	0.89	0.29	**0.80**	0.41	*0.95*	*1.00*	*0.95*		*0.99*	*1.00*	0.17
CR EQ (I,I)	0.84	0.24	0.75	**0.48**	*0.97*	*0.99*	*0.97*	*0.99*		*0.99*	0.12
CR HH (I,I)	0.91	0.32	0.82	**0.39**	*0.93*	*1.00*	*0.93*	*1.00*	*0.99*		0.19
CR Min	0.41	**0.65**	**0.45**	**0.19**	0.04	0.17	0.04	0.17	0.12	0.19	

CR: characterization results; EQ: ecosystem quality: HH: human health; and Min: mineral extraction.

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